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Some Concepts Pertaining to Investigative Methodology for Subsurface Process Research

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SOME CONCEPTS PERTAINING TO INVESTIGATIVE METHODOLOGY FOR SUBSURFACE PROCESS RESEARCH

by

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water and greatly simplified the sampling procedure.

The native ground water in the aquifer was more than tenfold higher in chloride content than the injected wastewater. Therefore, movement of injected water through the aquifer was traced by decreases in chloride concentrations of ground water at the observation wells. Ground water samples from the observation wells were analyzed periodically during the recharge operation for several halogenated organic compounds present at low concentrations in the injected water to establish breakthrough curves for these compounds. Retardation of movement of the compounds due to sorption on the aquifer solids was determined by comparison of their breakthrough curves at specific observation wells with analogous breakthrough curves for injected water.

There was no evidence for transformation within the aquifer of any of the monitored compounds during the period of wastewater injection. At those observation wells where complete breakthrough occurred, these compounds were present in concentrations essentially the same as in the injected water. However, there was reason to question if the residence times of the monitored compounds in the aquifer between the injection and observation wells were sufficiently long to permit detection of slowly occurring transformations. Therefore, selected halogenated organic compounds were monitored for one year after cessation of wastewater injection at an observation well in a portion of the aquifer which had been saturated in regard to sorptive capacity for these compounds during the injection operation. Significant decreases in concentrations of the monitored compounds during this time were concluded to be the result of transformation processes. The only other plausible explanation for the observed concentration decreases, dilution, was precluded because ground water flow in the region was shown by isotope tracer studies to be

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16. ABSTRACT

Problems of investigative methodology comprise a critical and often preponderant element of research to delineate and quantitate processes which govern the transport and fate of pollutants in subsurface environments. Examination of several recent research studies illustrates that both laboratory and field (in-situ) methodologies are useful in subsurface processes research, but also clearly shows that such research involves formidable methodological problems which result primarily from the nature of terrestrial subsurface environments. Such environments are usually remote and relatively inaccessible. This causes major methodological problems in acquiring authentic, uncontaminated samples of water and/or solids for analysis and microcosm construction. Subsurface environments are also highly structured and often exhibit significant heterogeneity across relatively short distances, which causes difficulties in determining proper locations for sample acquisition and in simulating subsurface environments in the laboratory. Finally, slow rates of movement and long residence times of water and pollutants within subsurface environments are responsible for methodological problems associated with the need to detect and characterize processes occurring at very slow rates. Advances in a number of diverse areas, including particularly geophysical methods, analytical procedures, microcosm technology, and drilling, coring, and well completion techniques, are required for needed improvements in methodology for subsurface processes research.

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Abstract

Problems of investigative methodology comprise a critical and often preponderant element of research to delineate and quantitate processes which govern the transport and fate of pollutants in subsurface environments. Examination of several recent research studies illustrates that both laboratory and field (in-situ) methodologies are useful in subsurface processes research, but also clearly shows that such research involves formidable methodological problems which result primarily from the nature of terrestrial subsurface environments. Such environments are usually remote and relatively inaccessible. This causes major methodological problems in acquiring authentic, uncontaminated samples of water and/or solids for analysis and microcosm construction. Subsurface environments are also highly structured and often exhibit significant heterogeneity across relatively short distances, which causes difficulties in determining proper locations for sample acquisition and in simulating subsurface environments in the laboratory. Finally, slow rates of movement and long residence times of water and pollutants within subsurface environments are responsible for methodological problems associated with the need to detect and characterize processes occurring at very slow rates. Advances in a number of diverse areas, including particularly geophysical methods, analytical procedures, microcosm technology, and drilling, coring, and well completion techniques, are required for needed improvements in methodology for subsurface processes research.

Introduction

When public concern regarding environmental pollution began to be translated into action in the U.S. during the early 1960's, relatively extensive efforts directed toward protection of the quality of air and surface water resources were initiated. The ground water resource, however, remained largely out of sight and out of mind, with only a very few scientists and engineers voicing concern that human activities might adversely affect ground-water quality. Within the past few years, this concern has been vindicated, as it has become quite clear that pollution of ground water is a major environmental problem that must be addressed if the quality of of this valuable and irreplacable resource is to be protected from serious degradation. At the same time, it has become equally apparent that effective and economical protection of ground water quality is likely to be achieved only if it is based on definitive knowledge of the transport and fate of pollutants in the subsurface, including both the unsaturated soil profile and underlying saturated formations. Consequently, research to delineate and quantitate the processes which govern the transport and fate of pollutants in subsurface environments is of paramount importance in providing the scientific base required for effective control of ground-water pollution.

As in any scientific endeavor, progress in environmental processes research is dependant on the development and application of methodology appropriate for investigation of the phenomena of interest. Investigations of processes which govern transport and fate of pollutants in the terrestrial subsurface involve especially formidable problems in methodology, primarily because of the relative remoteness and highly structured nature of the

environments in which these processes occur. Consequently, problems of investigative methodology comprise a critical and often preponderant element of research pertaining to subsurface transport and fate processes, and these problems must be effectively addressed if such research is to be successful.

This paper discusses three relatively recent research studies pertaining to the transport and fate of pollutants in subsurface environments which are illustrative both of methodological concepts useful for investigating subsurface processes and of inadequacies and problems of such methodologies.

Studies Illustrative of Methodologies for Investigating Subsurface Processes

Biotransformation Studies Employing Small-Scale Laboratory Microcosms

Wilson et al. (1983) have recently utilized small, relatively simple laboratory microcosms to investigate the biotransformation of selected organic chemicals in several subsurface environments. The microcosms consisted of 35ml or 50ml screw-top test tubes filled with authentic, uncontaminated aquifer material and closed with Teflon-lined screw caps.

Aquifer solids were obtained from the subsurface by special coring and extrusion procedures which precluded contamination by surface microorganisms. A bore hole was first drilled to the desired depth with an auger. A barrel equipped with a core retainer (Figure 1) was then placed on the bottom of the hole and pushed into the underlying undisturbed formation. The core thus obtained was extruded by hydraulic ram through a sterile paring device which removed the outer layer of the core that was contaminated by contact with the core barrel (Figure 2). A short length (3-5cm) of material from each end of the core was also removed and discarded because of possible contamination. The core material was extruded directly into sterile glass containers and transported to the laboratory for processing as quickly as possible.

For microcosm preparation, aquifer solids were mixed with a small quantity of sterile ground water to produce a slurry and transferred to sterile 35ml or 50ml screw top test tubes. Sufficient space was left in each tube for 1ml of dose solution consisting of the chemicals to be studied dissolved in filter-sterilized ground water. The tubes were topped off with dose solution to leave no head-space and sealed with Teflon-lined caps. The dose solution was dispersed throughout the microcosms with a vortex mixer. Abiotic control microcosms were prepared in the same manner, except that the core material was autoclaved (4 hr at 121°C) before dispensing into tubes.

A number of microcosm units were prepared for each experiment, and at least two test units and one control were analyzed initially and at selected intervals (e.g. 1,3, and 9 weeks) after incubation in the dark at appropriate aquifer temperature. Figure 3 shows a microcosm and apparatus employed for sampling. After removal of the cap, the microcosm tube was screwed into a closed 10mm bore Teflon stopcock. A tube containing pure water was then screwed into the other end of the stopcock and the cock was opened. The contents of the tubes were mixed with a vortex mixer, the cock was closed, and the tubes were removed and sealed with Teflon-lined screw caps. After centrifugation to settle solids, the diluted pore water was analyzed by appropriate methods.

This methodology has been employed with apparent success for investigating biotransformation processes in several subsurface environments, using various organic pollutants (Wilson et al., 1983; Wilson et al., 1984). Except for water movement, it appears to simulate subsurface environments with relative veracity, and probably is reasonably effective in transferring subsurface biotransformation processes to the laboratory where they can be more easily studied. However, there are several concerns and problems which

must be recognized in utilizing such methdology.

First, authentic core material, uncontaminated by surface microorganisms, must be acquired from the subsurface environments of interest for microcosm construction. The methodology is thus difficult and expensive, since costly drilling and coring operations using special equipment and techniques are required, as noted above. Studies of subsurface biotransformation processes have been attempted in the laboratory using microcosm systems constructed only with well water (Ehrlich et al., 1962) or with sterilized sand re-inoculated by perfusion with well water (Horvath and Elkin, 1978). However, since there is strong reason to doubt that microbial populations of well water are truly representative of populations occurring in aquifer solids, it is very questionable if these methods are effective in faithfully simulating subsurface environments and, hence, in transferring the biotransformation processes as they occur in the aquifer to the laboratory. Further study of these questions is needed, since elimination of the need for acquiring authentic uncontaminated core materials for microcosm construction would greatly simplify subsurface biotransformation studies.

A second concern in using this methodology is the extent to which the microbial population in a core and, hence, biotransformation processes which will occur in microcosms constructed from this core material, will be representative of the subsurface environment of interest. This is a manifestation of spatial variability problems that plague all investigations of subsurface pollution. Because of the rigid, highly structured nature of the geologic solids matrix comprising the framework of subsurface environments, such environments may exhibit very significant heterogeneity over short distances, both laterally and with depth. Although available information indicates that

microbial populations in subsurface regions below the root zone are remarkably uniform in numbers (Wilson and McNabb, 1983), it is highly probable that these populations will often vary significantly in types of organisms, metabolic capabilities, and levels of activity within relatively short distances. For example, microbial populations within lenses of less permeable material within an aquifer are likely to differ in composition and level of activity from populations in the bulk of the aquifer which experience a greater influx of water and, consequently, nutrients and electron acceptors. Similarly, populations within a plume of pollution in an aquifer will likely differ in composition and metabolic capability from populations in the surrounding pristine aquifer material because of adaptation to or inhibition by the pollutants. Hence, if core material for study of biotransformation in an aquifer happened to be obtained from such a lense or plume, the results would not truly reflect the biotransformation processes occurring in the aquifer as a whole.

A third concern and problem with this methodology is related to sensitivity. Because of the difficulty and expense involved in acquiring core material for microcosm construction, these systems are necessarily small, and the volumes of water which can be obtained from them for analysis are limited. Hence, very sensitive analytical methods are required for study of the biotransformation of chemicals at environmentally relevant concentrations using this methodology. Limitations of presently available analytical procedures, however, may cause the methodology to lack sufficient sensitivity to detect and characterize biotransformations occurring at rates that are very slow but that are still likely to be of much importance in subsurface environments because of slow water movement and concomitant long pollutant residence times therein. This was illustrated by Wilson et al. (1984) in work on the

pollution of ground water by polynuclear aromatic compounds at the site of an abandoned wood creosoting plant. Since the site was rather well characterized hydrologically, it was possible to use a mathematical model to estimate the concentrations of naphthalene that would be present in ground water at a boundary 200m from the point of entry over the next 100 years, assuming various rates of biodegradation. These estimates indicated that a degradation rate as low as 5 percent per year would have a substantial effect on the amount of naphthalene reaching the boundary. However, the lowest rate of biotransformation that could be detected using small scale microcosms constructed from core material from the site was approximately 50 percent per year.

Another concern with the methodology is the absence of any means for controlling redox potential in the microcosms. Use of this methodology to date has been primarily for simulating shallow water table aquifers that usually contain low levels of oxygen. In this roll the methodology appears adequate over a period of a few weeks, but over longer periods changes in redox would likely become intolerable.

Finally, an additional potential problem with the methodology is related to the possible contribution to pollutant biotransformation of consortia of microbes living symbiotically in microhabitats within subsurface environments. The slurrying of core material required for microcosm preparation would destroy microhabitats present in the subsurface solids and thus disrupt biotransformation processes mediated by such consortia.

Transport and Fate Study Employing Laboratory Soil Profile Models

Piwoni et al. (1984) have recently employed methodology involving the use of relatively complex laboratory microcosm systems for investigating processes controlling transport and fate of pollutants in an unsaturated soil profile receiving municipal wastewater amended with selected toxic chemicals.

Microcosms were prepared by packing 10cm increments of soil obtained with great care from a natural sandy soil profile into 15cm diameter borosilicate glass columns. The increments occupied the same relative positions in the columns as they did in the native profile. The soil was neither dried nor screened and was packed into the columns as soon after collection as possible to protect the native biota. The columns were packed to a depth of 150cm, with great care being exercised to achieve uniformity between columns and to attain a hydraulic conductivity essentially the same as that of the native profile.

Figure 4 shows schematically a column and associated components which comprised a complete microcosm system. A closed greenhouse section extended 45cm above the soil surface to provide room for growth of grass and permit recovery of compounds volatizing from the profile. The greenhouse was illuminated with artifical sunlight for 12 hours daily, with the remainder of the column being wrapped in metal foil to prevent light from contacting the soil profile below the surface. A low flow of air, sufficient to replace the air in the greenhouse approximately every eight minutes, was passed continuously through this section. A portion of the exiting air was passed through a trap containing Tenax GC to recover for analysis compounds which

volatilized from the soil profile.

Wastewater was mixed with an aqueous solution of test chemicals in a mixing reservoir prior to application to the soil. The solution of test chemicals, prepared aseptically in filter sterilized organic-free water, was stored without headspace in a flexible Teflon bag connected to the mixing reservoir by glass tubing and contained inside a sealed glass flask filled with water. An appropriate quantity of the chemical solution was forced into the mixing reservoir by pumping a measured volume of water into the sealed flask, thus displacing an equal volume of solution from the Teflon bag. The amended wastewater was transferred to the column by siphoning action initiated by applying pressure to the mixing reservoir with nitrogen gas. The mixing and application operations, as well as the lighting sequence for the greenhouse, were microprocessor controlled.

Water in the unsaturated soil profile was sampled by applying a gentle vacuum (30kPa) to sintered glass suction samplers in sampling ports in the wall of the column at depths of 7.5, 15, 30, and 60cm below the soil surface. For analysis of highly volatile compounds, the water sample was collected in a screw top test tube, with a trap containing Tenax GC located on the suction side of the test tube to scavenge volatiles escaping from solution. Both the contents of the tube and trap were analyzed. For analysis of extractable compounds, water from the suction samplers was passed directly through traps containing XAD resin to recover the compounds of interest. Samples of effluent water from the column and influent water from the mixing reservoir were also collected for analysis.

In this study, seven microcosm systems were operated. To simulate high rate infiltration land treatment systems, 4.4cm of wastewater was applied to each column daily, with equal portions being applied at 4 hr intervals. Three columns served as controls and received only wastewater for the duration of the experiment (58 weeks). Three columns received unamended wastewater for 18 weeks to allow the soil to acclimate to the wastewater constituents, and then received wastewater amended with selected toxic chemicals for 40 weeks. A seventh column received spring water amended with ammonium nitrate (to support plant growth) for 18 weeks, and then received spring water amended with ammonium nitrate and toxic chemicals for the duration of the study. The purpose of this column was to provide insight regarding the effect of the organic matter and inorganic nutrients of the wastewater on the behavior of toxic chemicals in the soil profile. Since the primary objective of the study was to investigate volatilization and transformation of toxic chemicals, interpretive monitoring was not initiated until 12 weeks after application of water or wastewater amended with toxic chemicals had begun, at which time the sorptive capacity of the columns for the test compounds had been essentially satisfied and steady-state conditions had been attained.

As used by Piwoni et al. (1984), this methodology appears to have been quite effective for investigation of volatilization and transformation processes occurring in the soil profile. With slight changes in experimental chronology, it could also have been employed for investigation of sorption processes. The methodology is, however, obviously very complex and costly, which is a major problem and concern in its utilization. Extensive fabrication of costly glassware and other components is required in constructing the microcosms. Proper aquisition of appropriate soil profile increments and packing of

effective columns is a major undertaking. In particular, preparation of soil columns that are uniformly packed and conform to the parent soil profile in hydraulic and other properties is somewhat of an art, and will usually require the services of an experienced and talented soil scientist. Also, utilization of this methodology will usually involve long periods of operation and the generation of very heavy analytical loads, with concommittant heavy resource and personnel requirements.

Another problem and concern with this methodology pertains to potential inadequacies in preserving the properties of natural soil profiles in the microcosms. The column packing procedure used in the methodology is probably fairly successful in producing in the column a soil profile which is a reasonable fascimile of a natural profile of sandy, non aggregated soil. It would, however, be inapplicable to soil with any appreciable aggregate structure, since such structure would be destroyed in the packing process. A method which captures undisturbed natural soil profiles for use in laboratory studies of subsurface processes would be much preferred.

Difficulties in distinguishing between transformation processes are also inherent to this methodology because of problems encountered in eliminating all biological activity in the columns without altering other soil properties and the cost and effort required to set up sterile control microcosms. In addition, there are problems in detecting and characterizing processes that occur at slow rates, but that may be important in subsurface environments. If the rate of water application to the column is decreased to increase pollutant residence time in the soil, the opportunity for detecting slow processes will be increased but the length of the experiment is likely to become prohibitive. Similarly, if column length is increased in an effort

to detect and characterize slow processes, operational problems and costs are likely to become unacceptable.

Field Study of Pollutant Transport and Fate in the Saturated Zone

During recent years, considerable research has been conducted at Stanford University pertaining to the effects on ground water quality of recharging an aquifer by direct injection of reclaimed municipal wastewater. Roberts et al. (1982) have reported on aspects of this work which involved field (in-situ) investigation of processes governing the transport and fate of organic pollutants in saturated subsurface environments.

This research was conducted in an aquifer composed of a layer of relatively homogeneous silty sand ranging in thickness from 1.5 to 3m and located at a depth of 10-15m below the surface of the ground. The formation was underlain by an impermeable clay layer and overlain by relatively impermeable, interbedded layers of clay and silty sand. Tertiary wastewater was injected directly into the aquifer though a recharge well, and the effects on ground water were monitored at several strategically located observation wells. An aquifer section indicating the relative locations of the recharge and observation wells is shown schematically in Figure 5.

Observation wells were drilled by means of a hollow stem auger to avoid the use of drilling fluid which might contaminate the aquifer and interfere with subsequent ground-water sampling. The wells were cased with 2cm diameter threaded polyethylene tubing connected without adhesives which might also cause contamination problems. In most wells, the casing was slotted through the full length of the permeable zone. Pressure in the aquifer during recharge was sufficient to ensure artesian flow of the monitoring wells. This precluded the need for pumping to obtain samples of ground

extremely slow, and because the rates of decrease for different compounds, which should have been very similar had they resulted only from dilution, were also different.

This field (in-situ) investigation was relatively effective in detecting and providing insight regarding sorption and transformation processes affecting pollutant transport and fate in the subsurface. There were several major and relatively unique factors which contributed to this success. These included: the unusual degree of experimental control afforded by the confined, well defined, relatively homogenous aquifer in which the study was conducted; the natural tracer system for water movement provided by the large difference in chloride content of the injected water and native aquifer water; and, simplified sampling of the observation wells permitted by the artesian flow of water from the aquifer. Such a fortuitous set of circumstances is not often encountered in field studies. Nevertheless, if this investigation is examined objectively, a number of problems and concerns pertaining to field (in-situ) methodologies for subsurface processes research can be discerned.

First, such methodologies require the sampling of subsurface waters at a sufficient number of locations within the area of study to clearly define water and pollutant movement and to detect meaningful concentration changes. This usually requires installation of a number of costly sampling wells capable of providing representative, uncontaminated ground water samples. Special drilling techniques that do not contaminate the aquifer must be used, and materials for well casing and completion must be consistent with the objectives of the study, neither adding any interfering substances to samples through leaching nor removing any constituents through sorption or other mechanisms. Also, pumps and other equipment used for obtaining samples of

ground water from the wells must be both non-contaminating and non-sorbing.

A second problem in field methodologies pertains to difficulties in determining locations for sampling points, both in the horizontal plane and in depth, due to frequent heterogeneity of subsurface environments across relatively short distances. Thus, if a sampling well is drilled in a location or screened at a depth which is wrong by only a very few meters, a plume of polluted ground water may be missed entirely. Unlike an analogous situation in air or surface water studies, this will be a very costly mistake, since drilling and completion of an additional expensive well will be required to achieve the necessary change in location of the sampling point.

Another problem is the need to employ tracer substances in field studies to accurately determine water movement in the subsurface. Such substances must behave essentially the same as water molecules in subsurface environments, being neither retarded in movement by sorption on subsurface solids nor attenuated in concentration by transformation processes. Unfortunately, substances which can serve effectively as tracers often cannot be introduced into the subsurface for experimental purposes because of possible deleterious effects on ground water quality, and seldom are present naturally at appropriate concentrations in subsurface waters, as was the case in the study described above.

Difficulty in distinguishing between processes responsible for changes in pollutant concentrations is yet another concern in field methodologies for subsurface process studies In the study described above, decreases in concentrations of selected halogenated hydrocarbons which occurred over a prolonged period of observation and could not be attributed to other processes provided strong evidence for transformation of these substances in the aquifer.

However, there was no basis for determining if these transformations resulted from biological processes, or if abiotic processes were partly or wholly responsible. Obviously, establishing a sterile control system in a field situation is usually a very remote possibility. Similarly, it is often difficult to determine if the failure of a pollutant to appear in significant concentrations at an obsevation well over a prolonged period of observation is due to transformation of the compound in the aquifer between tne source and observation well, or is the result of sorption or dispersion processes.

Additional readily apparent problems and concerns with field methodologies for subsurface process research pertain to needs for detection and characterization of processes occurring at very slow rates and for replication and repetition of experiments. Field investigation of processes that occur at very slow rates in subsurface environments, but that may be important because of long pollutant residence times therein, requires monitoring of pollutant concentrations over long periods of time and/or over long distances of pollutant travel. This is likely to be excessively expensive because of the need for prolonged field and supporting laboratory operations and installation of many costly observation wells. Also, there is usually little opportunity in field studies to replicate or repeat experiments. Because of physical limitations, it is usually almost impossible to establish two or more identical experimental systems for investigation of subsurface processes in field situations. Also, by the time an initial experiment has been completed in a field study of subsurface processes, the experimental system is likely to have undergone sufficient change, primarily as the result of exposure to pollutants, to preclude exact repetition of the experiment.

Conclusions

The investigations outlined above demonstrate a few of the methodological concepts employed in research pertaining to the processes governing transport and fate of pollutants in the terrestrial subsurface, and are indicative of many of the major methodological problems encountered in such research. These investigations clearly show that both laboratory and field (in-situ) methodologies are useful in subsurface processes research. It is obvious that laboratory methodologies possess advantages over field methodologies in regard to cost, labor requirements, control of variables, and opportunity for replication and repetition of experiments. However, there are numerous uncertainties concerning the effectiveness of laboratory methodologies in transferring subsurface processes from the field to the laboratory and, hence, the extent to which process information gained by use of such methodologies is truly reflective of in-situ processes. Subsurface processes research is likely to be most effective if both laboratory and field methodologies can be employed simultaneously and in a complimentary manner, with laboratory studies being used to guide and confirm field work.

The studies described above also clearly reiterate that research pertaining to subsurface transport and fate processes, whether conducted in the laboratory or the field, will almost invariably involve formidable methodological problems. Thus, such research will likely be very laborious and expensive, particularly in comparison to analogous research in other environmental media.

The major problems in investigative methodology for subsurface processes research appear to result primarily from three principal characteristics of the terrestrial subsurface. The first, and perhaps dominant, of these

characteristics is remoteness and difficult accessibility. The acquisition of authentic, uncontaminated samples of water and/or solids from remote and relatively inaccessible subsurface environments is required for both laboratory and field investigations of subsurface transport and fate processes, either for construction of laboratory microcosms or for field monitoring activities. This entails special problems in drilling and completion of sampling wells, coring operations, and sampling apparatus and techniques.

A second characteristic of the subsurface contributing significantly to methodological problems in subsurface processes research is the highly structured nature and attendant heterogeneity across relatively short distances of subsurface environments. This characteristic is a principal cause for difficulties in preserving the properties of parent subsurface environments in laboratory microcosm systems, and is responsible for problems in determining the proper locations for obtaining cores of subsurface solids to ensure that laboratory microcosms constructed from these materials will be representative of the subsurface compartments of interest. It is also the cause for difficulties in determining the proper location for sampling points which will permit effective observation of subsurface transport and fate of pollutants in field investigations.

Finally, the characteristically slow rate of movement of water and pollutants in subsurface environments, which usually results in long residence times for pollutants within these environments, necessitates that methodologies for subsurface processes research possess the capability for detecting and characterizing processes which occur at very slow rates. Hence, this characteristic is largely responsible for methodological problems pertaining to sensitivity and long term operation of experimental systems in both laboratory and field studies.

Obviously, there is need for much improvement in investigative methodologies for research pertaining to the processes that govern transport and fate of pollutants in subsurface environments. Advances in a number of diverse areas, including particularly geophysical methods, chemical analysis procedures, microcosm technology, and drilling, coring, and well completion techniques, will be required to accomplish this improvement.

This paper has been reviewed in accordance with the U.S. Environmental Protection Agency's peer and administrative review policies and approved for presentation and publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

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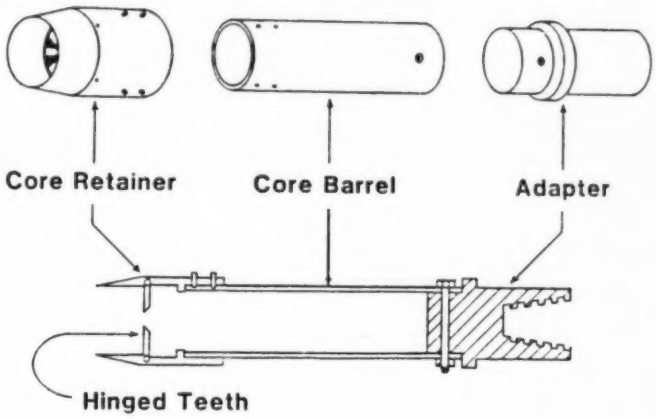

Figure 1. Coring device. (After Wilson et al., 1983)

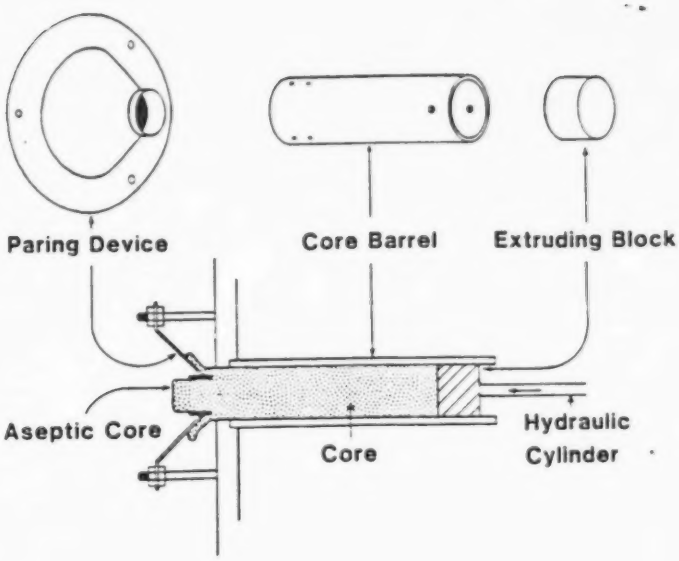

Figure 2. Device to recover cored material aseptically. (After Wilson et al., 1983)

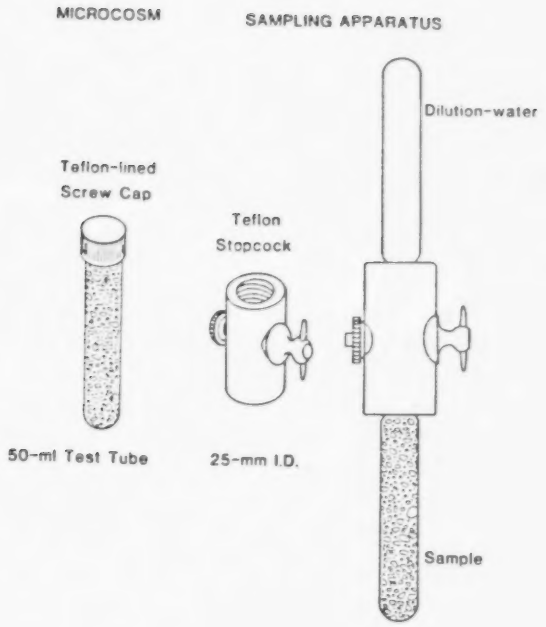

Figure 3. Microcosm and sampling device. (After Wilson et al., 1983)

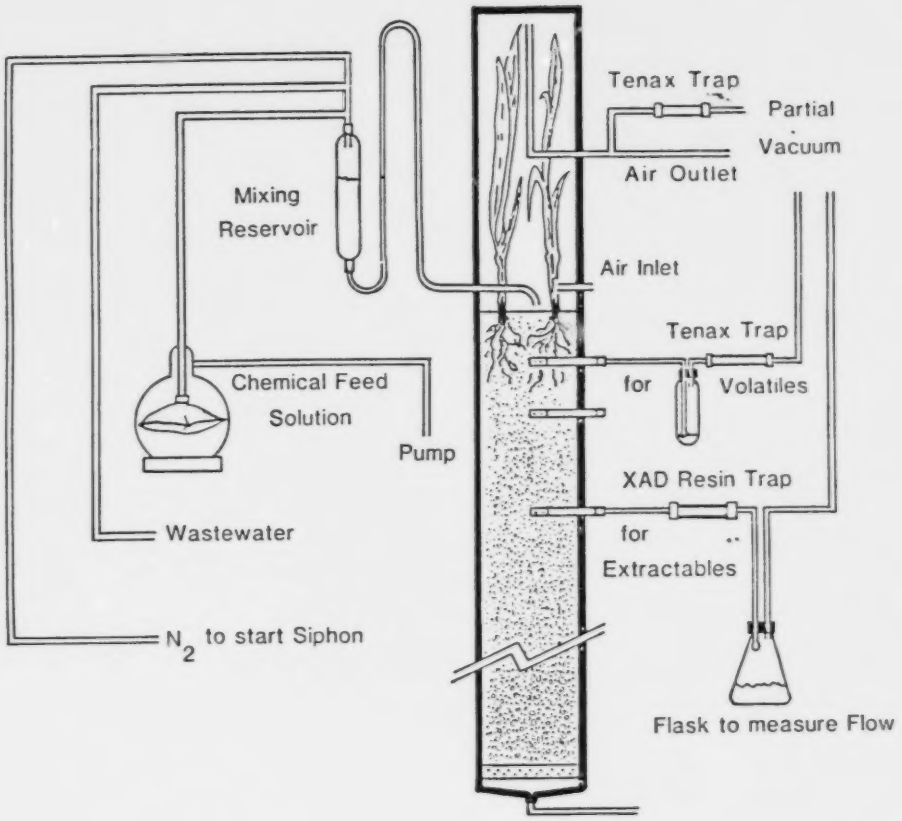

Figure 4. Soil profile microcosm system. (After Piwoni et al., 1984)

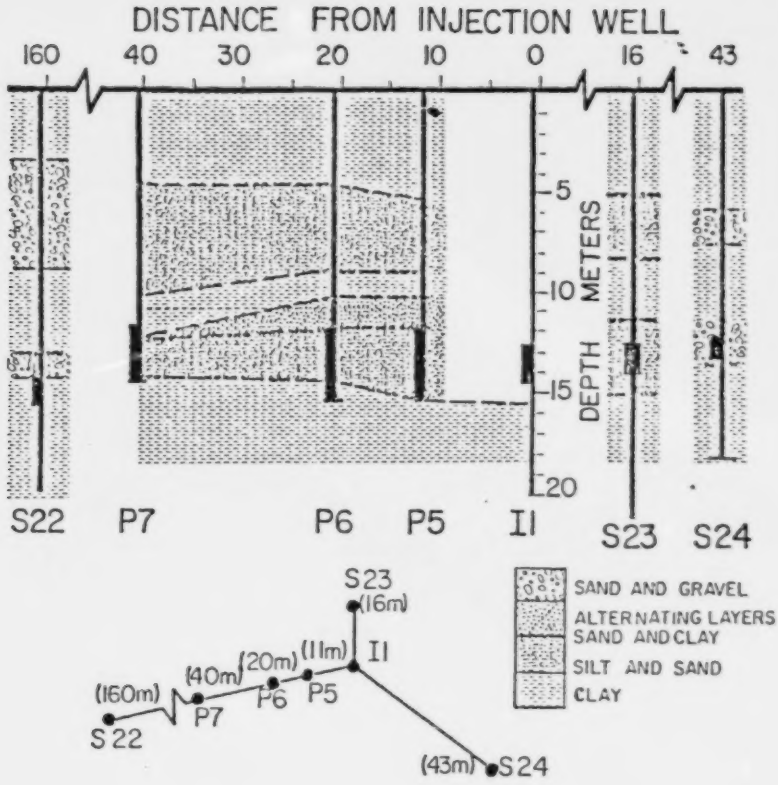

Figure 5. Aquifer section showing relative locations of wells at recharge site. (After Roberts et al., 1982)